

The Case for an Accelerating Universe from Supernovae

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ABSTRACT

The unexpected faintness of high-redshift Type Ia supernovae (SNe Ia), as measured by two teams, has been interpreted as evidence that the expansion of the Universe is accelerating. We review the current challenges to this interpretation and seek to answer whether the cosmological implications are compelling. We discuss future observations of SNe Ia which could offer extraordinary evidence to test acceleration.

subject headings: supernovae: general—cosmology: observations

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1. Introduction

Two teams have presented observational evidence from high-redshift type Ia supernovae (SNe Ia) that the expansion of the Universe is accelerating, propelled by vacuum energy (Riess et al. 1998; Perlmutter et al. 1999). The primary evidence for this hypothesis is the faintness of distant SNe Ia relative to their expected brightness in a decelerating Universe. The question we propose to answer in this review is whether the observations of distant supernovae *compel* us to conclude that the expansion is accelerating.

2. Supernova Measurements

2.1. Past Work

Supernovae (SNe) have a long history of employment in the quest to measure Hubble’s constant (see Branch 1998 for review) and currently provide a column of support for a strong consensus that $H_0=60$ to $70 \text{ km s}^{-1} \text{ Mpc}^{-1}$. The history of utilizing supernovae to measure the time evolution of the expansion rate is far briefer. All initial proposals for using high-redshift SNe to constrain global deceleration recognized the necessity of an optical space telescope to collect the data. Wagoner (1977) envisioned application of Baade’s method or the the Expanding Photosphere method (Kirshner & Kwan 1974) to measure the angular diameter distance of Type I (hydrogen-deficient) and Type II (hydrogen-rich) supernovae at $z = 0.3$. Colgate (1979) demonstrated even greater prescience, suggesting that SNe I at $z = 1$ could be used as standard candles for “determining the cosmological constant with greater accuracy than other standard candles.” Further thoughts by Tammann (1979) included the necessity to account for the redshift of the observed light using spectrophotometry of SNe in the ultraviolet (i.e., K -corrections), host galaxy extinction, and time dilation of the light curves.

Yet even before the launch of the *Hubble Space Telescope (HST)*, a persistent two-year ground-based effort by a Danish group was rewarded by the discovery of their first (and only reported) high-redshift SN Ia, SN 1988U at $z = 0.31$ (Norgarrd-Nielsen et al. 1989) as well as modest bounds on the deceleration parameter, $-0.6 < q_0 < 2.5$. This team employed modern image processing techniques to scale the brightness and resolution of images of high-redshift clusters to match previous images and looked for supernovae in the difference frames. Unfortunately, the project’s low discovery rate coupled with the dispersion of SNe Ia when treated as perfect standard candles ($\sim 0.5 \text{ mag}$) suggested that the determination of the deceleration parameter would require a scientific lifetime.

However, great progress was made by the Supernova Cosmology Project (SCP) in the detection rate of high-redshift SNe Ia by employing large-format CCDs, large-aperture telescopes, and more sophisticated image-analysis techniques (Perlmutter et al. 1995). These advances led to the detection of seven SNe Ia at $z \approx 0.4$ between 1992 and 1994, yielding a confidence region that suggested of a flat, $\Lambda = 0$ universe but with a large range of uncertainty (Perlmutter et al. 1997).

The High- z Supernova Search Team (HZT) joined the hunt for high-redshift SNe Ia with their discovery of SN 1995K at $z = 0.48$ (Schmidt et al. 1998). Both teams made rapid improvements in their ability to discover ever greater numbers of SNe Ia at still larger redshifts. One-time redshift record holders included SN 1997ap at $z = 0.83$ (SCP; Perlmutter et al. 1998), SN 1997ck at $z = 0.97$ (HZT; Garnavich et al. 1998a), SN 1998eq at $z = 1.20$ (SCP; Aldering et al. 1998) and SN 1999fv at $z=1.23$ (HZT; Tonry et al. 1999).

Before either teams’ claimed samples of high-redshift SNe Ia were large enough to detect the acceleration signal, both teams found the data to be inconsistent with a Universe closed by matter (Garnavich et al. 1998a; Perlmutter et al. 1998).

Record redshift Type Ia Supernovae			
SN Ia	z	discoverers	discovered
SN 1988U	0.31	Nørgaard-Nielsen-Nielsen et al; IAUC 4641	8/1988
SN 1992bi	0.46	SCP; IAUC 5652	4/1992
SN 1995K	0.48	HZT; IAUC 6160	3/1995
SN 1995at	0.66	SCP; IAUC 6270	12/1995
SN 1996cl	0.83	SCP; IAUC 6621	3/1996
SN 1997ap	0.83	SCP; IAUC 6596	3/1997
SN 1997ck*	0.97	HZT; IAUC 6646	4/1997
SN 1998eq	1.20	SCP; IAUC 7046	10/1998
SN 1999fv	1.23	HZT; IAUC 7312	11/1999

* Poor spectrum of SN but light curve consistent with SN Ia at measured z of host

These observational feats were preceded by increased understanding and ability to make use of SNe Ia observations to constrain the cosmological parameters. Empirical correlations between SN Ia light curve shapes and peak luminosity improved the precision of distance estimates beyond the standard candle model (Phillips 1993; Hamuy et al. 1995; Riess, Press, Kirshner 1995; Perlmutter et al. 1995; Tripp 1997; Saha et al. 1999; Parodi et al. 2000). Studies of SN Ia colors provided the means to distinguish supernovae which were reddened by dust from those which were intrinsically red (Riess, Press, Kirshner 1996; Riess et al. 1998; Phillips et al. 1998; Tripp & Branch 1999). Goobar & Perlmutter (1995) showed that measurements of SNe Ia at different redshift intervals could break degeneracies between Ω_M and Ω_Λ . Additional work on cross-filter K -corrections provided the ability to accurately transform the observations of high-redshift SNe Ia to the rest-frame (Kim, Goobar, & Perlmutter 1996).

2.2. Observations

In order to resolve whether the results from high-redshift SNe Ia are compelling it is important to review how the measurements were obtained.

Both the SCP and the HZT detected their samples of high-redshift SNe Ia by using large-format CCDs at telescopes with large apertures (most commonly the CTIO 4-m Blanco telescope). Using two sets of deep images in the R or I -band spaced across a lunation, the “template” images are subtracted from the second-epoch images and automated software searches for sources in the difference images whose intensity surpasses a specific threshold. The observations taken in pairs are spaced over a small time interval of a few minutes to eliminate moving transients. Human inspectors “filter” the automated results in an effort to maximize the likelihood that candidates are supernovae (Schmidt et al. 1998; Perlmutter et al. 1999). Because the resources available for collecting spectral identifications for all the candidates are insufficient, candidates which appear most likely to be SNe Ia are given priority. The factors which are favored in the human selection criteria include candidates which are separated from the host galaxy nuclei and those

that show good contrast with the host galaxy (especially those with little or no apparent host). The signal-to-noise ratios of the identifying spectra vary greatly (Perlmutter et al. 1995, 1998; Riess et al. 1998) but have improved with the availability of the Keck Telescope and an increased emphasis on the search for clues of SN Ia evolution. Most of the spectral identifications were made by visual comparison to template spectra of nearby SNe Ia. More recently automated cross-correlation techniques have been employed (Riess et al. 1997). Approximately half of the SN Ia redshifts were determined from narrow emission lines or Ca H and K absorption; the rest were derived from the broad supernova features. Although formal statistics are not currently available, we are aware that the SCP candidates have yielded a greater fraction of SNe Ia than the HZT candidates, a significant number of which turn out to be SNe II. Taken together, about half of the two teams’ candidates are revealed to be SNe Ia, with the rest classified as SNe II, AGNs, flare stars, or unclassified objects. SNe Ia in the desired redshift range are monitored photometrically in two colors by observatories around the world using red-sensitive passbands; *HST* has monitored the light curves of about two dozen of these objects.

The initial search template images are eventually replaced by deeper template images obtained with good seeing and taken one or more years after discovery when the SNe Ia have faded by five to eight magnitudes. More recently, repeated searching of the same fields has provided deep template images *before* the SN explosion. After the SN images are bias corrected and flat-fielded they are geometrically aligned, and the resolution and intensity are scaled to match those of the templates. After subtracting the host galaxy light the SN magnitudes are measured. The SCP uses aperture photometry; the HZT fits point-spread-functions. Uncertainties are determined synthetically by the injection of artificial SNe of known brightness. The SCP uses standard passbands and Landolt (1982) standards of comparison while the HZT uses a custom passband system which is transformed to the Landolt scale (Schmidt et al. 1998). Custom cross-band *K*-corrections are calculated using spectrophotometry of nearby SNe Ia whose colors are reddened to match the high-redshift objects.

The distances are measured by fitting empirical families of light curves to the flux observations of individual supernovae. The measured distances are derived from the luminosity distance,

$$D_L = \left(\frac{\mathcal{L}}{4\pi\mathcal{F}} \right)^{\frac{1}{2}} \quad (1)$$

where \mathcal{L} and \mathcal{F} are the SN’s intrinsic luminosity and observed flux, respectively and D_L is in Mpc. Alternately, a logarithmic luminosity distance (i.e., the distance modulus) is used:

$$\mu = m - M = 5 \log D_L + 25, \quad (2)$$

where M is the SN’s absolute magnitude and m is the observed magnitude in a given passband.

Three different light-curve fitting methods have been used to measure the distances, each of which determines the shape of the best-fitting light curve to identify the individual luminosity of the SN Ia. The HZT has used both the multi-color light-curve shape method (MLCS; Riess, Press, & Kirshner 1996; Riess et al. 1998) and a template fitting approach based on the parameter $\Delta m_{15}(B)$ (Phillips 1993; Phillips et al. 1999), while the SCP uses the “stretch method” (Perlmutter et al. 1995; 1999).

Nearby SNe Ia provide both the measure of the Hubble flow and the means to calibrate the relationship between light-curve shape and luminosity. The SCP uses ~ 20 nearby SNe Ia in the Hubble flow from the Calán/Tololo Survey (Hamuy et al. 1996) while the HZT adds to this set an equal number of SNe from the CfA Sample (Riess et al. 1999).

Dust extinction is handled somewhat differently by the two teams. The HZT measures the extinction from the $B - V$ reddening (i.e., the color excess) and then combines this measurement in a Bayesian formalism using a prior host galaxy extinction distribution calculated by Hatano, Branch, & Deaton (1998). This treatment assumes that extinction makes supernovae appear dimmer (farther), never brighter (closer). The SCP uses a number of different approaches (including the HZT approach), but favors making no individual extinction corrections and discarding outliers. Figure 1 shows a single Hubble diagram made with the data from both teams (Riess et al. 1998; Perlmutter et al. 1999).

The measured distances are then compared to those expected for their redshifts as a function of the cosmological parameters Ω_M , Ω_Λ , and H_0 :

$$D_L = cH_0^{-1}(1+z)|\Omega_k|^{-1/2} \text{sinh}\{|\Omega_k|^{1/2} \int_0^z dz [(1+z)^2(1+\Omega_M z) - z(2+z)\Omega_\Lambda]^{-1/2}\}, \quad (3)$$

where $\Omega_k = 1 - \Omega_M - \Omega_\Lambda$, and sinh is \sinh for $\Omega_k \geq 0$ and \sin for $\Omega_k \leq 0$ (Carroll, Press, & Turner 1992). The likelihoods for cosmological parameters are determined by minimizing the χ^2 statistic between the measured and predicted distances (Riess et al. 1998; Perlmutter et al. 1999). Determination of Ω_M and Ω_Λ are independent of the value of H_0 or the absolute magnitude calibration of SNe Ia. The confidence intervals in the Ω_M - Ω_Λ plane determined by both teams are shown in Figure 2. In this plane, acceleration is defined by the region where the deceleration parameter, q_0 , is negative,

$$q_0 = \frac{\Omega_M}{2} - \Omega_\Lambda < 0. \quad (4)$$

2.3. Results

The visual impression from Figure 2 is that the supernova observations favor the parameter space containing a positive cosmological constant and an accelerating Universe with high statistical confidence. The confidence regions determined by the two teams are in remarkably good agreement. Both teams claim that these results do not result from chance with more than 99% confidence (Riess et al. 1998; Perlmutter et al. 1999). However, the specific confidence of these cosmological conclusions depends on which parameter space intervals one considers to be equally likely, *a priori*. This point is addressed by Drell, Loredo, & Wasserman (2000) who suggest that models with $\Omega_\Lambda=0$ and $\Omega_\Lambda \neq 0$ could be considered equally probable, *a priori*. While Riess et al. (1998) and Perlmutter et al. (1999) considered the probability that $\Omega_\Lambda > 0$ with a flat prior in a linear Ω_Λ space, an alternative is to use a flat prior in a *logarithmic* Ω_Λ space.

Another useful way to quantify the SN Ia constraints has been given by Perlmutter et al. (1999) as $0.8\Omega_M - 0.6\Omega_\Lambda = -0.2 \pm 0.1$, a result which applies equally well to the Riess et al. (1998) data.

A more illuminating way to quantify the evidence for an accelerating Universe is to consider how the SN Ia distances depart from decelerating or “coasting” models. The average high-redshift SN Ia is 0.19 mag dimmer or $\sim 10\%$ farther than expected for a Universe with no cosmological constant and negligible matter ($\Omega_\Lambda = 0$, $\Omega_M = 0$). Of course it’s apparent that the Universe has more than negligible matter and the current consensus from the mass, light, X-ray emission, numbers, and motions of clusters of galaxies is that $\Omega_M \approx 0.3$ (Carlberg et al. 1996; Bahcall, Fan, & Cen 1997; Lin et al. 1996; Strauss & Willick 1995). The high-redshift SNe Ia from both teams are 0.28 mag dimmer or 14% farther than expected in a Universe with this much matter and no cosmological constant. The *statistical* uncertainty of these values is 0.08 and 0.06 mag (or 4% and 3% in distance) for the HZT and SCP, respectively. The observed dispersion of the

high-redshift SNe Ia around the best-fit cosmology is 0.21 mag for the HZT and 0.36 mag for the SCP. A frequentist would consider the accelerating Universe to be statistically likely at the 3σ to 4σ level (i.e., $> 99\%$), while the Bayesian likelihood would depend on a statement of the natural space and scale for Ω_Λ .

Simply put, high-redshift SNe Ia are ~ 0.25 mag fainter than expected in our Universe with its presumed mass density but without a cosmological constant (or which is not accelerating). The statistical confidence that SNe Ia are fainter than expected is high enough to accept that it does not result from chance and additional SNe Ia continue to support this conclusion (Schmidt 2000). Rather, this result is only challenged by systematic uncertainties not reflected in the variance of high-redshift SN Ia distance measurements. In the following sections we review the challenges to the cosmological interpretation of the SN Ia observations and consider whether the evidence compels us to believe that the Universe is accelerating.

3. Challenges and Tests of the Accelerating Universe

3.1. Evolution

Could SNe Ia at $z = 0.5$, a look-back time of ~ 5 Gyr, be intrinsically fainter than nearby SNe Ia by 25%? For the purpose of using SNe Ia as distance indicators near and far, we are concerned only with an evolution which changes the luminosity of a SN Ia for a fixed light-curve shape. Evolution is a major obstacle to the measurement of cosmological parameters, having plagued workers who tried to infer the global deceleration rate from brightest cluster galaxies in the 1970s (Sandage & Hardy 1973). We will consider both the theoretical and empirical indications for SN Ia evolution.

Theoretical understanding of SNe Ia provides reasons to believe that evolution is not a challenge to the accelerating Universe. SNe Ia are events which occur on stellar scales, not galaxian scales, and therefore should be less subject to the known evolution of stellar populations. However, our inability to conclusively identify the progenitor systems (see Livio 2000 for a review) and our lack of a *complete* theoretical model (see Leibundgut 2000 for a review) means we cannot rely exclusively on theory to rule out the critical degree of evolution.

Nevertheless, theoretical calculations can provide some insight into this question. Höflich, Wheeler, & Thielemann (1998) have calculated models of spectra of SNe Ia with solar and one-third solar metallicities and have found little difference between the spectral energy distribution over the wavelengths where the SNe Ia have been observed (see Figure 3). In principle, changes in the age and hence initial mass of the progenitor star at high redshift could yield white dwarfs of varying carbon-to-oxygen (C/O) ratio. It is currently difficult to assess if such a variation could produce significant evolution as these calculations lack the necessary precision (Dominguez et al. 1999; von Hippel, Bothun, & Schommer 1997). Umeda et al. (1999) suggest that a change in the C/O ratio is the source of the inhomogeneity in SN Ia luminosity, but they conclude that calibration of the luminosity via light-curve shape relations effectively inoculates the cosmological measurements to an evolution in the C/O ratio.

To date, answers to the question of whether SNe Ia evolve have been sought from empirical evidence. In the nearby sample, SNe Ia are observed in a wide range of host-galaxy morphologies including ellipticals, post-starburst galaxies (e.g., SN 1972E in NGC 5253), low surface brightness galaxies (e.g., SN 1995ak in IC 1844), irregulars (e.g., SN 1937C in IC 4182), S0s (e.g., SN 1995D in NGC 2962), and early to late-type spirals (van den Bergh 1994; Cappellaro et al. 1997; Hamuy et al. 1996; Riess et al. 1999). The range of metallicity, stellar age, and interstellar environments probed by the nearby hosts is much greater than the

mean evolution in these properties for individual galaxies between $z = 0$ and $z = 0.5$. Some variation in the observed characteristics of SNe Ia with host morphology has been seen in the nearby sample (Hamuy et al. 1996; Branch, Romanishin, & Baron 1996). Yet *after correction* for the light-curve shape/luminosity relationship and extinction, the observed residuals from the Hubble flow do not correlate with host galaxy morphology (see Figure 4). In addition, Hubble flow residuals show no correlation with the projected distance from the host center (see §3.6). This evidence suggests that SN Ia distance estimates are insensitive to variations in the supernova progenitor environment and is the strongest argument against significant evolution to $z = 0.5$ (Schmidt et al. 1998). However, this evidence is still circumstantial as we cannot be sure that the *local* environments of the SN Ia progenitors are similar to the *average* environments of the hosts. Future studies which probe the local regions of nearby SNe Ia should be able to explore their variance.

The other empirical test of evolution has been to compare the observed characteristics of low-redshift and high-redshift SNe Ia. The assumption of this test is that a luminosity evolution of $\sim 25\%$ would be accompanied by other visibly altered characteristics of the explosion. Here too our lack of firm theoretical footing makes it difficult to gauge the correspondence between any evolution in distance-independent quantities and luminosity. Therefore we must conservatively demand that observations of *all* observables of distant SNe Ia be statistically consistent with the nearby sample.

3.1.1. Spectra

Comparisons of high-quality spectra between nearby and high-redshift SN Ia, such as those seen in Figure 5, have revealed remarkable similarity (Riess et al. 1998; Perlmutter et al. 1998, 1999; Filippenko et al. 2000). The spectral energy distribution is sensitive to the atmospheric conditions of the supernova (i.e., temperature, abundances, and ejecta velocities). Even primitive modeling indicates that it would be difficult to retain the primary features of the SN Ia spectrum while altering the luminosity by about 20% to 30%. Further, comparisons of temporal sequences of spectra reveal no apparent differences as the photosphere recedes in mass (Filippenko et al. 2000), indicating that the superficial similarities persist at deeper layers. However, among the variety of nearby SNe Ia are objects which are both $\sim 25\%$ fainter than the average and also display very typical spectral features (e.g., SN 1992A, see Figure 5). Therefore, the existing spectral test alone is not sufficient to check for this degree of evolution.

While spectral similarity between nearby and distant SNe Ia provides no indication of evolution, a *lack* of any spectral peculiarities among high-redshift SNe Ia could signal some changes at high redshift. Li et al. (2000) find from the most unbiased survey of nearby SNe Ia to date that $\sim 20\%$ of SNe Ia are spectroscopically similar to the overluminous SN 1991T. SN 1991T-like objects show weak Ca II, Si II, and S II, but prominent features of Fe III (Filippenko 1997), and close cousins, such as SN 1999aa, have similar characteristics with the exception that Ca II absorption is more normal. Monte Carlo simulations of the search criteria used by the SCP and the HZT team performed by Li, Filippenko, & Riess (2000) indicate that such overluminous objects should comprise approximately 25% of high-redshift SNe Ia (with some uncertainty due to a possible link between such objects and circumstellar dust). To date, neither team has reported the existence of a single SN 1991T-like object among ~ 100 high-redshift objects.

It is certain that the low signal-to-noise ratio of the spectra of high-redshift SNe Ia, coupled with the redshifting of spectral features out of the observable window makes it more difficult to identify individuals from this peculiar class. In addition, the spectroscopic peculiarities of SN 1991T-like objects

are only apparent close to maximum light (or earlier), and some high-redshift SNe Ia may not have been observed early enough to identify their spectral peculiarities. This same effect may also explain why the Calán/Tololo survey of 29 SNe Ia yielded no SN 1991T-like objects (Hamuy et al. 1996). If, however, these observational biases are not to blame, the absence of SN 1991T-like SNe Ia at high redshift could result from an evolution of the population of progenitor systems (see Livio 2000 for a review) or a subtle difference in selection criteria (see §3.6). If true, this type of evolution may yield important clues which help identify the progenitor systems (Ruiz-Lapuente & Canal 1998), but it is unlikely to affect the measurement of the cosmological parameters since spectroscopically normal SNe Ia at low and high redshift have been used to derive the cosmological constraints.

3.1.2. Broad-band

The distributions of light-curve shapes for nearby and distant SNe Ia are statistically consistent (Riess et al. 1998; Perlmutter et al. 1999). Such consistency appears to extend to infrared light curves of high-redshift SNe Ia which show the characteristic second maximum of typical, low-redshift SNe Ia (Riess et al. 2000).

An analysis by Drell et al. (2000) indicates that different light-curve *fitting methods* may not be statistically consistent and that the apparent differences may be a function of the light curve shape. However, these conclusions are highly sensitive to estimates of the *correlated* distance uncertainties between different fitting methods and these correlated uncertainties are difficult to estimate.

Evolutionary changes in the model temperature and hence the thermal output of the explosion could be detected from the colors of pre-nebular supernovae. The most significant analysis of $B - V$ colors, performed by Perlmutter et al. (1999), demonstrated consistency between low and high-redshift SNe Ia at maximum light. Likewise, Riess et al. (2000) found that the $B - I$ colors of a SN Ia at $z = 0.5$ were consistent with those of nearby SNe Ia. However, Falco et al. 1999 (see also McLeod et al. 1999) suggested that the $B - V$ colors of high-redshift SNe Ia from the HZT may be excessively blue, a conclusion which cannot be rejected by the $B - I$ color measurements by Riess et al. (2000). More data are needed to confirm or refute this possibility. If true, this could indicate either evolution or the existence of a halo of Milky Way dust which would redden the observed wavelengths of nearby SNe Ia more than redshifted objects. This latter possibility has been suggested by recent Milky Way dust maps of Schlegel, Finkbeiner, & Davis (1999) in contrast to the previous maps of Burstein & Heiles (1982), but it would augment rather than fully explain the faintness of distant SNe Ia.

The risetime (i.e., the time interval between explosion and maximum light) is sensitive to the ejecta opacity and the distribution of ^{56}Ni . The risetime of nearby SNe Ia (Riess et al. 1999b) and the high-redshift SNe Ia of the SCP (Goldhaber 1998; Groom 1998) were initially strongly discrepant (Riess et al. 1999c). However, a reanalysis of the SCP high-redshift data by Aldering, Knop, & Nugent (2000) finds the high-redshift risetime to be longer and much more uncertain than indicated by Groom (1998). The remaining difference could be no more than a $\sim 2.0\sigma$ chance occurrence. More early photometry of distant SNe Ia is needed to increase the significance of this test of evolution.

Evolution is arguably the most serious challenge to the cosmological interpretation of high-redshift SNe Ia. Further studies, currently underway, seek to compare the host galaxy morphologies and luminosity versus light-curve shape relations for nearby and distant SNe Ia. The results reviewed in this section do not appear to provide any clear evidence of evolution. However, absence of evidence is not necessarily

evidence of absence. The paucity of high signal-to-noise ratio observations of high-redshift SNe Ia and the current lack of a comprehensive theoretical model or a well-understood progenitor system keeps the embers of skepticism aglow.

3.2. Dust

Consideration of a non-cosmological explanation for the dimming of distant supernova light must invariably turn to a famous pitfall of optical astronomy: extinction. Trouble has often followed dust in astronomy, a point first appreciated by Trumpler (1930) when analyzing the spatial distribution of Galactic stars.

3.2.1. Ordinary Dust

An additional $\sim 25\%$ opacity of visual light by dust in the light paths of distant supernovae would be sufficient to nullify the measurement of the accelerating Universe. Both teams currently measure SN Ia colors to correct for the ordinary kind of interstellar extinction which reddens light. Galactic extinction maps from Burstein & Heiles (1982) and Schlegel, Finkbeiner, & Davis (1998) were used by the HZT and the SCP, respectively, to correct individual SNe Ia for Milky Way extinction. Such corrections were typically less than 0.1 mag due to the high galactic latitudes of the SNe Ia. Even a previously unknown halo of Galactic dust would dim the restframe light of nearby SNe Ia more than highly redshifted SNe Ia and would therefore not explain the cosmological indications.

Measurements of $B - V$ colors have been used by both teams to test for and remove host galaxy extinction (Riess et al. 1998; Perlmutter et al. 1999; see Figure 6). Totani & Kobayashi (1999) have suggested that the remaining uncertainty in the mean measured $B - V$ color excess ($\sigma = 0.02$ mag; Perlmutter et al. 1999), when multiplied by reddening ratios of 3 to 4 to determine the optical opacity, may be too large to discriminate between open and lambda-dominated cosmologies with high confidence. However, such concern seems unwarranted as this uncertainty remains 3 to 4 times smaller than the size of the cosmological effect of an accelerating Universe.

Another measurable effect of the critical amount of mean interstellar extinction is that it would introduce more dispersion in the distance measurements than is currently observed. A random line of sight into a host galaxy will intersect a nonuniform amount of extinction. Hatano, Branch, & Deaton (1998) have calculated the expected distribution of extinction along random lines of sight into host galaxies. A mean, uncorrected extinction of 0.25 mag would induce twice the distance dispersion observed by the HZT (Riess et al. 1998). In addition, high-redshift surveys are biased towards finding SNe Ia which have even less extinction than would be expected from the distributions of Hatano et al. (1998).

A more powerful way to search for reddening by dust is to observe high-redshift SNe Ia over a large wavelength span: from the optical to the infrared. Infrared color excesses would be more than twice as large as E_{B-V} for ordinary dust. A set of such observations for SN 1999Q ($z = 0.46$) disfavor $A_V = 0.25$ mag of dust with Galactic-type reddening at high confidence (Riess et al. 2000), but more SNe Ia need to be observed in the near-infrared to strengthen this conclusion.

3.2.2. Grey Dust

More pernicious than ordinary dust is “grey” dust which could leave little or no imprint on the spectral energy distribution of SNe Ia. Perfectly grey dust is only a theoretical construct, but dust which is grayer than Galactic-type dust (i.e., larger reddening ratios) does exist (Mathis 1990) and could challenge the cosmological interpretation of high-redshift SNe Ia.

Grey dust can be made with large spherical dust grains or elongated “whiskers.” Past studies of whiskers (Aguirre 1999a; Rana 1979, 1980) indicate that they would distort the cosmic microwave background (CMB), an effect which has not been seen. Like non-grey extinction, grey interstellar extinction does not provide an acceptable explanation for the dimness of SNe because the inherent variations in the opacity along random lines of sight would induce more distance dispersion than is observed (Riess et al. 1998).

Grey *intergalactic* extinction could affect measurements of the deceleration parameter (Eigenson 1949) without tell-tale dispersion or reddening. Indeed, observations of neither SNe Ia nor other astrophysical objects rule out a 30% opacity by large semi-spherical dust grains (Aguirre 1999b). Aguirre (1999a,b) has shown that a uniformly distributed component of intergalactic grey dust with a mass density of $\Omega_{dust} \approx 5 \times 10^{-5}$ and graphite grains of size $> 0.1 \mu\text{m}$ could explain the faintness of high- z SNe Ia without detectable reddening and without overproducing the currently unresolved portion of the far-infrared (far-IR) background. However, this physical model of dust would provide some reddening which can readily be detected with observations in the optical and infrared. Measurements by Riess et al. (2000; see Figure 7) of E_{B-I} for a single high-redshift SN Ia disfavor a 30% visual opacity of grey dust at the $\sim 2.5\sigma$ confidence level, but more observations are needed to strengthen this conclusion. Additional studies of the faint far-IR sources seen with SCUBA may soon provide definitive constraints on the unresolved component of the far-IR background and the viability of extragalactic grey dust.

3.3. Gravitational Lensing

The inhomogeneous distribution of matter in the Universe typically deamplifies and very rarely amplifies the observed brightness of distant SNe Ia compared to the average. (Note that the *mean* observed brightness must equal the unamplified value expected in a perfectly smooth Universe.)

The size of the typical deamplification is a function of the SN Ia redshift, the mass density of the Universe and the fraction of dark matter locked into compact objects. This effect has been quantified by a wide range of techniques (Kantowski, Vaughan, & Branch 1995; Frieman 1997; Wambsganss et al. 1997; Holz & Wald 1998; Kantowski 1998; Metcalf 1999; Barber 2000). The effect of weak lensing on the observed distribution of luminosities of SNe Ia at $z = 1$ and $z = 0.5$ can be seen in Figure 8. In the most relevant regime for the current SNe Ia at $z = 0.5$ (i.e., $\Omega_M \approx 0.3$, and mostly diffuse dark matter) the typical deamplification is $\sim 2\%$, much smaller than the cosmological effect. An extreme case (i.e., $\Omega_M \approx 0.5$, all matter in point masses) could deamplify the median SN Ia at $z = 0.5$ by 5% (Holz 1998), but this model is unlikely to be correct and the effect is still not large enough to negate the cosmological interpretation of high-redshift SNe Ia. Perlmutter et al. (1999) considered lensing by up to $\Omega_M = 0.25$ in compact material in the determination of their confidence intervals. They found little impact on the likelihood of a positive cosmological constant (see Figure 9). Wang (2000) suggests that by flux-averaging (i.e., binning the SNe Ia distances by redshift) one can reduce the bias due to weak lensing. In the future, any bias due to weak lensing will naturally vanish as the sample sizes become larger and the mean observed luminosity more robust. It is interesting and potentially useful to note that the observed distribution of SN Ia distances (see

Figure 8) can in principle be used to determine the fraction of gravitating matter contained in compact objects (Seljak & Holz 1999; Metcalf & Silk 1999).

3.4. Measurement Biases

In this section we consider if biases in the measurement process of high-redshift SNe Ia could mimic the evidence for an accelerating Universe. An exhaustive list of such biases has been considered by Hogg (2000) and Hogg & Turner (1998). Here we discuss how these biases may apply to the supernova measurements.

The observational challenge is to measure the distance to high-redshift SNe Ia which are 6 to 7 magnitudes fainter and have lower signal-to-noise ratio than those which delineate the Hubble flow. Differences in the way low and high-redshift SNe Ia are observed must not introduce biases in their distance measures at more than the few percent level. Indeed, Hogg (2000) has noted that the proximity of high-redshift SNe Ia to any reasonable world model is a testament to the feasibility of measuring distances across such a large range. However, because the goal of these observations is precision cosmology (and not simply to demonstrate the dynamic range of useful photometry) our scrutiny must be greater.

Charge transfer inefficiency (CTI) and detector non-linearities can cause faint objects to appear fainter. However, ground-based observations of high-redshift SN Ia are limited by the bright sky, a regime in which these effects are widely found to be negligible. For space-based observatories such as the *Hubble Space Telescope*, CTI is far more troublesome but quite correctable (Whitmore, Heyer, & Casertano 1999). In addition, only a subset of the high-redshift SNe Ia have been measured with *HST* and the cosmological conclusions do not depend on the inclusion of these objects.

High precision, flux-conserving algorithms have been developed to properly subtract images of the host galaxy from images with SN light (Alard & Lupton 1998). Correctly employed, these methods reduce any biases in the measurement of the SN brightness to less than a few percent. Tests for measurement biases and estimates of uncertainty are performed by both teams by the injection of artificial SNe into the observed images.

Hogg & Turner (1998) discuss a bias towards higher observed fluxes which naturally occurs when measuring the brightness at discovery of low signal-to-noise ratio sources. This bias results from the preferential selection of faint sources on the bright side of the Poisson distribution of photon statistics. Follow-up observations of the source would not incur this bias. This effect would have little impact on the supernova distances measured by the HZT and SCP because the light curves are dominated by observations made *after* discovery. In addition, the direction of this effect is opposite to the signal of an accelerating Universe. However, this effect may become more important for SNe Ia found at $z > 1$ for which the discovery observation may provide one of the most significant measurements.

3.5. Selection Biases

Do the HZT and SCP preferentially select faint SNe Ia at high redshift? Because we have already considered evolution in §3.1, here we are only concerned with the characteristics of a high-redshift sample which is drawn from the *same* population as the nearby sample. In so doing, we must also consider if the nearby sample is a fair representation of that population.

As an example, consider the set of nearby SNe Ia which appear fainter than expected for their redshift in the bottom panel of Figure 1. Presumably these objects appear dim due to the intrinsic random scatter of SNe Ia. If, however, these SNe Ia had a characteristic in common which, in addition, favored their discovery at high-redshift, a bias would result. To date, no such characteristic has been identified and the observed dispersion of nearby SNe Ia is consistent with their measurement errors.

Howell, Wang, & Wheeler (2000) found a difference between the projected distances from the hosts’ centers for the nearby and distant SNe Ia (see Figure 10). Many of the nearby SNe Ia were found in the photographic Calán/Tololo survey in which saturated galaxy cores masked SNe near their hosts’ centers (Shaw 1979; Hamuy & Pinto 1999). The result is that distant SNe Ia are more centrally located than the nearby sample. However, in an analysis of 44 nearby SNe Ia, Riess et al. (1999) found no dependence of the distance measurement on the projected distance from the host center, so this selection effect appears to have no bearing on the cosmological use of SNe Ia (see Figure 11).

Malmquist bias (Malmquist 1924; 1936) can shift the mean distance too close in a magnitude-limited survey of SNe Ia. This effect seems to contrast with the cosmological dimming perceived in an accelerating Universe. However, if the *nearby* sample were more afflicted by Malmquist bias than the distant sample, this bias could mimic an accelerating Universe. Because the intrinsic scatter of SN Ia distances is low (≤ 0.15 mag), Malmquist bias, which scales with the square of the dispersion (see Mihalas & Binney 1981 for a derivation), is small for SNe Ia. Perlmutter et al. (1999) made analytic calculations of Malmquist bias arising from the intrinsic dispersion of SNe Ia (assumed to be 0.17 mag) and the SCP search incompleteness (determined empirically) to estimate that the *net* bias between the samples is no more than 0.03 mag. [Perlmutter et al. (1999) notes that the net bias may actually be closer to zero due to a compensating bias against the selection of light curves which are “fast” for their luminosity and therefore spend less time above the detection limit.] Riess et al. (1998) used a Monte Carlo exercise to simulate the selection of SNe Ia near and far. Inputs to this exercise included the time interval between successive search epochs, limiting magnitudes, observed light-curve shapes, and the distribution of SN Ia luminosities. They report a net bias of less than 0.01 mag. These results indicate that the *net* Malmquist bias has negligible impact on the cosmological conclusions.

3.6. Alternative Cosmological Models

The conclusions drawn from high-redshift SNe Ia are predicated on a model with two free parameters, Ω_M and Ω_Λ , and a Friedmann-Robertson-Walker cosmology. In the absence of a sound fundamental motivation for $\Omega_\Lambda \approx \Omega_M$, alternate and more general descriptions of an energy density with negative pressure have been suggested (Caldwell, Dave, & Steinhardt 1998). These phenomenological or “quintessence” models invoke a decaying scalar field rolling down a potential as the source of today’s acceleration (Wang et al. 2000). A distinction of these models from a cosmological constant is that w , the ratio of pressure to energy density, is between -1 and 0, whereas w is exactly -1 for a cosmological constant. For feasible quintessence models, w , the equation-of-state parameter, varies slowly with time and can be approximated today by a constant equal to

$$\tilde{w} \approx \int da \Omega_Q(a) w(a) / \int da \Omega_Q(a), \quad (5)$$

where a is the scale factor and Ω_Q is the energy density of the vacuum component. The current acceleration for these models (assuming only two significant energy components today, Ω_M and Ω_Q) is

$$q_0 = -\ddot{a}(t_0)a(t_0)/\dot{a}^2(t_0) = \frac{1}{2}(\Omega_M + \Omega_Q(1 + 3w)), \quad (6)$$

and is generally less than for a cosmological constant (all other parameters fixed). Inspection of equation (2) reveals that the Universe is accelerating if q_0 is negative ($\ddot{a}(t_0)$ is positive), requiring that $w < -\frac{1}{3}$, independent of the value of Ω_M .

Can we determine if the expansion is accelerating in a quintessence model? The SN Ia data from Perlmutter et al. (1999) and Riess et al. (1998) already provide meaningful constraints on w (Garnavich et al. 1998b; Perlmutter et al. 1999). Increasing the value of w from -1 (i.e., for a cosmological constant) reduces the acceleration provided by a fixed value of Ω_Q , but larger values of Ω_Q are needed to retain an acceptable fit to the data. Graphically, increasing w from -1 rotates the error ellipses in Figure 2 to favor lower values of Ω_M and greater values of Ω_Q . As seen from equation (6), the line separating an accelerating and decelerating Universe rotates in the same direction (always anchored at $\Omega_M = 0$ and $\Omega_Q = 0$), providing no gain on an acceptable region of parameter space which is not accelerating. The nearest intersection between a non-accelerating region of parameter space and one which is preferred by the data remains when $\Omega_M \ll 1$ and $\Omega_Q \ll 1$. However, values near $\Omega_M = 0$ and $\Omega_Q = 0$ are poor fits to the data independent of the value of w .

Perhaps the simplest way to understand why the SN Ia data favor an accelerating Universe is to consider an FRW cosmology with $\Omega_M = 0$ and no vacuum energy. This empty Universe must be neither accelerating nor decelerating but simply coasting. The fact that the high-redshift SNe Ia are systematically farther for their redshift than expected in this cosmology means that the distance between low and high-redshift SNe Ia (where redshift is a surrogate for time) grew *faster* than expected for a Universe which has been coasting on today's Hubble expansion. This implies that the Universe has been accelerating.

An alternate cosmological explanation to acceleration has been posited by Goodwin et al. (1999) and Tomita (2000). They suggest that the supernova data are also consistent with a decrease in the Hubble expansion by 10-20% beyond $z = 0.1$ ($300h^{-1}$ Mpc). The distance at which the Hubble expansion dips would correspond to the approximate radius of the “local” underdensity in which we live. Although a few peculiar flow surveys support bulk motions on scales up to half this size (Lauer & Postman 1994; Hudson et al. 1999), most recent surveys do not (Dale et al. 1999; Courteau et al. 2000; Colless et al. 1999; Riess et al. 1999; see Willick 2000 for a review). However, the biggest problem with such a commodious, local underdensity is its great improbability. Power spectra demonstrate (Watkins & Feldman 1995; Feldman & Watkins 1998) that the density of the Universe is extremely homogeneous on this scale, and finding ourselves in the midst of such a vacuous location would be virtually anti-Copernican. Using cold dark matter power spectra constrained by CMB observations and large scale structure, Shi and Turner (1998) and Wang, Spergel, and Turner (1998) expect 0.5% to 1.5% variations in the Hubble constant on $300h^{-1}$ Mpc scales, a factor of 20 times smaller than required in the local void model. By filling in the Hubble diagram of SNe Ia at $0.1 < z < 0.2$ it would be possible to test this model.

Outside the FRW cosmologies the SN Ia data can have significantly different interpretations. For example, in steady-state cosmologies, SN redshifts do not come from expansion, but rather through “tired-light” processes. However, the SN Ia data exhibit the time dilation effect expected in an expanding Universe, implying that the tired-light hypothesis is incorrect (Leibundgut et al. 1996; Goldhaber et al. 1996; Riess et al. 1997; but see Narlikar & Arp 1997). In the quasi-steady state cosmology, the SN Ia data lead to modifications of the model, such as matter creation during periodic expansion phases (Hoyle,

Burbidge, & Narlikar 2000). A detailed consideration of how to interpret the SN Ia data in non-FRW cosmologies is beyond the scope of this review, but is thoroughly addressed by Hoyle, Burbidge, & Narlikar (2000). Alternative theories of gravity such as modified Newtonian dynamics models (MOND; Milgrom 1983, 1998; McGaugh & de Blok 1998a,b) could also modify the interpretation of the observations of high-redshift SNe Ia.

4. Conclusion

After reviewing the cosmological interpretation of SN Ia observations and the current challenges to the analysis of the data, we can now offer an answer to the question initially posed: do the observations of distant supernovae *compel* us to conclude that the expansion of the Universe is accelerating?

With full consideration of the evidence, we conclude that an accelerating Universe remains the most *likely* interpretation of the data because the alternatives, individually, appear less likely. However, the quantity and quality of the SN Ia evidence *alone* is not yet sufficient to *compel* belief in an accelerating Universe. The primary sources of reasonable doubt are evolution and extinction, as discussed above. Although the types of studies also described above could potentially yield evidence that either of these non-cosmological contaminants is significant, the current absence of such evidence does not suffice as definitive evidence of their absence. Our current inability to identify the progenitors of SNe Ia and to formulate a self-consistent model of their explosions exacerbates such doubts. Even optimists would acknowledge that neither of these theoretical challenges is likely to be met in the near future.

Fortunately there are at least two routes to obtain compelling evidence to accept (or refute) the accelerating Universe, one of which employs the use of SNe Ia at even greater redshifts.

5. Epilogue

5.1. The Era of Deceleration

If the Universe is accelerating, it is a rather recent phenomenon likely commencing between $z \approx 0.4$ and 1. Before this time the Universe was more compact and the pull of matter dominated the push of vacuum energy in the equation of motion. As a result, the Universe at $z \geq 1$ must be *decelerating*. This cosmological signature should be readily apparent by extending the Hubble diagram of SNe Ia to $z \approx 1.2$. By this redshift SNe Ia in an accelerating Universe will cease to diverge in distance from an equally massive Universe without vacuum energy. Alternatively, if a monotonically increasing, systematic effect is the source of the excessive faintness of high-redshift SNe Ia, the measured distances of SNe Ia at $z \geq 1$ will continue to diverge from a cosmology without vacuum energy and in addition would diverge from the cosmological model inferred from SNe Ia at $z = 0.5$ (see Figure 12). Complex parameterizations of evolution or extinction selected to match both the accelerating and decelerating epochs of expansion would require a near conspiracy of fine tuning and are highly doubtful.

Efforts are already underway to find and measure SNe Ia at $z > 1$. Gilliland, Nugent, & Phillips (1999) used a subsequent epoch of the Hubble Deep Field to detect two SNe, one (SN 1997ff) with a photometric redshift of $z = 1.32$. The elliptical host of SN 1997ff suggests that this object is of Type Ia, but the observations are insufficient to provide a useful distance estimate. The SCP reported the discovery

of SN 1998ef at $z = 1.20$ (Aldering et al. 1998) and follow-up observations with the *HST* will provide a useful distance estimate (Aldering 2000). The HZT recently reported the discovery of four SNe Ia at $z > 1$ including SN 1999fv at $z = 1.23$ (Tonry et al. 1999). From this growing sample will likely come the means to search for the epoch of deceleration.

5.2. Cosmic Complements

We previously sought to determine if the observations of SNe Ia *alone* require an accelerating Universe. Now we will briefly consider the cosmological constraints provided by other astrophysical phenomena. A thorough discussion of these constraints is beyond the scope of this review but can be found elsewhere (Tyson & Turner 1999; Roos & Harun-or-Rashid 2000)

Current measurements of the cosmic microwave background (CMB) power spectrum indicate that the sum total of energy densities is within 10% of unity. This result is seen from the BOOMERANG (Melchiorri et al. 1999; Lange et al. 2000; de Bernardis et al. 2000), the TACO (Miller et al. 1999) and MAXIMA experiments (Hanany et al. 2000; Balbi et al. 2000) and from a compilation of all other CMB measurements (Tegmark & Zaldarriaga 2000). In addition, estimates of Ω_M from the mass, light, X-ray emission, numbers, and motions of clusters of galaxies converge around 0.2 to 0.3 (Carlberg et al. 1996; Bahcall, Fan, & Cen 1997; Lin et al. 1996; Strauss & Willick 1995). These two pieces of information alone indicate a significant contribution by vacuum energy, sufficient to produce an accelerating Universe (see Figure 13). Additional constraints from observations of the Lyman-alpha forest, cluster evolution, double radio galaxies, and statistics of gravitational lenses have been used to tighten these conclusions (Roos & Harun-or-Rashid 2000; Turner 1999; Eisenstein, Hu, & Tegmark 1999; Lineweaver 1998).

Although no single cosmological observation yields a conclusive census of the energy densities in the Universe, the combined constraints from multiple experiments is providing strong bounds on the cosmological parameters. Each individual experiment has unique sources of systematic uncertainty. By combining the results of many experiments it should be possible to negate their impact on the determination of the cosmological parameters.

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Figure Captions:

Figure 1: Hubble diagrams of SNe Ia from Perlmutter et al. (1999; SCP) and Riess et al. (1998; HZT). Overplotted are three cosmologies: “low” and “high” Ω_M with $\Omega_\Lambda = 0$ and the best fit for a flat cosmology, $\Omega_M = 0.3$, $\Omega_\Lambda = 0.7$. The bottom panel shows the difference between data and models from the $\Omega_M = 0.3$, $\Omega_\Lambda = 0$ prediction. The average difference between the data and the $\Omega_M = 0.3$, $\Omega_\Lambda = 0$ prediction is 0.28 mag.

Figure 2: SNe Ia joint confidence intervals for $(\Omega_M, \Omega_\Lambda)$ from Perlmutter et al. (1999; SCP) and Riess et al. (1998; HZT). Regions representing specific cosmological scenarios are indicated.

Figure 3: Type Ia supernova model spectral energy distributions for solar and $\frac{1}{3}$ metallicities. Superimposed are the transmission functions for standard passbands; from left to right is U, B, V , and R . From Höflich, Wheeler & Thielemann (1998)

Figure 4: The nearby Hubble diagram of SNe Ia in different host galaxy morphologies. In the top panel the SNe Ia are treated as standard candles and in the bottom panel distances are determined with the MLCS method (Riess, Press, & Kirshner 1996; Riess et al. 1998). After MLCS corrections are made, the distance Hubble flow residuals are independent of host galaxy morphology.

Figure 5: Spectra of 4 nearby and 1 high-redshift SN Ia at the same phase (Riess et al. 1998). Within the observed variance of SN Ia spectral features, the spectra of high-redshift SNe Ia are indistinguishable from the low-redshift SNe Ia. The spectra of the low-redshift SNe Ia were resampled and convolved with Gaussian noise to match the quality of the spectrum of SN 1998ai.

Figure 6: Comparison of color excess, E_{B-V} , for nearby SNe Ia from the Calan/Tololo survey (Hamuy et al. 1996a,b) and high-redshift SNe Ia from Perlmutter et al. (SCP; 1999). The color excesses at high and low redshift are consistent indicating negligible extinction and/or no evidence for color evolution.

Figure 7: The color evolution, $B - I$, and the color excess, E_{B-I} , of a high-redshift SN Ia, SN 1999Q ($Z = 0.46$), compared to the custom MLCS template curve with no dust and enough dust (of either Galactic-type or greyer) to nullify the cosmological constant. The smaller error bars are from photometry noise; the larger error bars include all sources of uncertainty such as intrinsic dispersion of SN Ia $B - I$ color, K -corrections, and photometry zeropoints. The data for SN 1999Q are consistent with no reddening by dust, moderately inconsistent with $A_V=0.3$ mag of grey dust (i.e., graphite dust with minimum size $> 0.1 \mu\text{m}$; Aguirre 1999a,b) and $A_V=0.3$ mag of Galactic-type dust. From Riess et al. (2000).

Figure 8: Probability distribution $P(\mu)$ for supernova apparent brightness μ normalized to $\mu = 1$ for a filled beam (i.e., a homogeneous Universe). The vertical lines are at the empty-beam value. “Galaxies” are treated as isothermal spheres and truncated at a radius of 380 kpc; “compact objects” are point masses. From Holz (1998.)

Figure 9: Cosmological constraints from Perlmutter et al. (SCP; 1999) for three weak lensing scenarios. Fit C assumes a filled beam, case K assumes an empty beam, and fit L is a model with weak lensing by up to $\Omega_M = 0.25$ in compact objects.

Figure 10: The projected distances from the host centers of nearby SNe Ia discovered photographically and with CCDs and high-redshift SNe Ia discovered with CCDs (Howell, Wang, & Wheeler 2000).

Figure 11: MLCS distance residuals from the Hubble flow for nearby SNe Ia versus their projected distance from their host centers (Riess et al. 1999a).

Figure 12: The Hubble diagram of SNe Ia (see Figure 1) and the effect of a systematic error which grows linearly with redshift (e.g., evolution or grey extinction).

Figure 13: Cosmological constraints from SNe Ia, CMB, and matter (Turner 1999).













